

# On the Origin of Entropic Gravity and Inertia

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It was recently suggested that quantum field theory is not fundamental but emerges from the loss of information about matter crossing causal horizons. On the basis of this formalism, Verlinde's entropic gravity and Jacobson's thermodynamic gravity are derived from the Unruh effect and the holographic principle. The holographic screen in Verlinde's formalism can be identified as local Rindler horizons and its entropy as that of the bulk fields beyond the horizons. This naturally resolves some issues on entropic gravity. The quantum fluctuation of the fields is the origin of the thermodynamic nature of entropic gravity. It is also suggested that inertia is related to dragging Rindler horizons.

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## I. INTRODUCTION

Studies of black hole physics have consistently implied a deep connection between gravity and thermodynamics [1]. This leads to Jacobson's proposal that Einstein's equation of general relativity can be derived from the first law of thermodynamics and the area-proportional Rindler horizon entropy [2]. Verlinde [3] recently proposed a remarkable new idea linking classical gravity to entropic forces in a rather heuristic way, which has attracted much interest [4–18]. He derived Newton's second law and Einstein's equation from the relation between the entropy of a holographic screen and mass inside the screen. Padmanabhan [19] also proposed that classical gravity can be derived from the equipartition energy of horizons.

My colleagues and I proposed a slightly different, but related idea connecting gravity to quantum information [20, 21] on the basis of Jacobson's model. We suggested that Einstein's equation can be derived from Landauer's principle by considering information loss at causal horizons. Furthermore, I showed [22] that quantum mechanics is not fundamental but emerges from the information loss and that it even leads to the holographic principle [23]. In this paper, it is suggested that the origin of Verlinde's formalism and Jacobson's model could be naturally explained by this information theoretic interpretation of quantum mechanics.

Inspired by the information theoretic nature of entropy we emphasized the possible role of information in gravity in a series of works [24–26]. For example, in Ref. [24], we showed that a cosmic causal horizon with a radius  $R_h$  and Hawking temperature  $T_h$  has a kind of thermal energy  $E_h \propto T_h S_h$  associated with holographic horizon entropy  $S_h \propto R_h^2$  linked with information loss, and this thermal energy (possibly cosmic Hawking radiation) could be dark energy. Using a similar approach the first law of black hole thermodynamics is derived from the second law of thermodynamics [25]. These works are based on the holographic principle saying that the number of independent degrees of freedom (DOF) in a region is proportional to its area and Landauer's principle. This dark energy theory predicts the observed dark energy equation of state and magnitude [24] and the zero cosmological constant [27]. (See [28–32] for similar approaches.) All these results imply that gravity has something to do with information.

Let us first briefly review Verlinde's formalism about classical mechanics. In the formalism, inspired by the holographic principle, it was conjectured that a holographic screen with energy  $E_h$ , temperature  $T$  and an area  $A$  satisfies the equipartition law of energy  $E_h = k_B T N / 2$ , where  $N = A / l_P^2$  is the number of bits on the screen,  $k_B$  is the Boltzmann constant, and  $l_P$  is the Planck length. Verlinde considered a particle with mass  $m$  approaching the screen and *assumed* that this motion brings the change of the entropy of the screen

$$\Delta S_h = \frac{2\pi c k_B m \Delta x}{\hbar}, \quad (1)$$

where  $\Delta x$  is the distance between the screen and the particle, and  $c$  is the light velocity. It is one of the key assumptions of the paper that allows the derivation of Newton's equation. Then, from the first law of thermodynamics,  $\Delta S_h$  results in a variation of the screen energy

$$\Delta E_h = T \Delta S_h = F \Delta x, \quad (2)$$

which can be interpreted to be the definition of the holographic entropic force  $F \equiv \Delta E_h / \Delta x$ . If we use the Unruh temperature

$$T_U = \frac{\hbar a}{2\pi c k_B} \quad (3)$$

for  $T$  and insert Eq. (1) into Eq. (2), we can immediately obtain the entropic force

$$F = \frac{\Delta E}{\Delta x} = T_U \frac{\Delta S}{\Delta x} = ma, \quad (4)$$

which is just Newton's second law. Amazingly simple arguments reproduced one of the most basic equation in physics from thermodynamics.

However, there appeared some criticisms [14, 28, 33, 34] on the assumptions Verlinde took. The most serious one seems to be about the origin of the entropy and its variation equation in Eq. (1). The usage of the second law of thermodynamics might imply the violation of the time reversal symmetry of gravity. Furthermore, according to the holographic principle, the entropy increase should be proportional to some area rather than the linear scale  $\Delta x$  as in Eq. (1). It is also questionable whether we can apply the holographic principle to arbitrary surfaces or whether we can associate the Unruh temperature with the surfaces. The usage of the Unruh temperature is obviously not a proof that the screen is actually the Rindler horizon. It should be appropriately justified by careful analysis. The physical DOF on the screen that has thermodynamics is unclear. Considering remarkable implications of Verlinde's theory, it is very important to understand the exact physical origin of Verlinde's holographic screen and its entropy.

To overcome these difficulties, we reinterpret Verlinde's entropic force in terms of the information theoretic model of quantum mechanics [22] recently suggested. This interpretation shall turn out to be consistent with not only Verlinde's formalism but also Jacobson's model [2] or quantum information theoretic model of gravity [20, 21]. The key idea in this paper is that for an accelerating object there is always an observer to whom the object seems to cross a Rindler horizon of the observer. In this paper we assume the holographic principle and the metric nature of the spacetime (but not the Einstein equation).

In Sec. II, the derivation of quantum and classical mechanics from information theory is reviewed. In Sec. III, a derivation of entropic gravity is presented. Sec. IV contains discussions.

## II. MECHANICS FROM INFORMATION LOSS

From my point of view the most original and important contribution of Verlinde's model is the thermodynamic interpretation of Newton's mechanics. In this section an information theoretic interpretation of this thermodynamic model is presented.

Let us review the information theoretic interpretation of quantum field theory (QFT) in Ref. [22]. Imagine an accelerating observer  $\Theta$  with acceleration  $a$  in the  $x_1$  direction in a flat spacetime with coordinates  $x = (t, x_1, x_2, x_3)$  (See Fig. 1). The corresponding Rindler coordinates  $\xi = (\eta, r, x_2, x_3)$  are

$$t = r \sinh(a\eta), \quad x_1 = r \cosh(a\eta). \quad (5)$$

Now, consider a scalar field  $\phi$  with Hamiltonian

$$H(\phi) = \int d^3x \left[ \frac{1}{2} \left( \frac{\partial \phi}{\partial t} \right)^2 + \frac{1}{2} (\nabla \phi)^2 + V(\phi) \right] \quad (6)$$

and a potential  $V$ . In the Rindler coordinate it becomes

$$H_R = \int_{r>0} dr dx_{\perp} ar \left[ \frac{1}{2} \left( \frac{\partial \phi}{\partial \eta} \right)^2 + \frac{1}{2} \left( \frac{\partial \phi}{\partial r} \right)^2 + \frac{1}{2} (\nabla_{\perp} \phi)^2 + V(\phi) \right], \quad (7)$$

where  $\perp$  denotes the plane orthogonal to  $(\eta, r)$  plane.

As the field crosses the Rindler horizon for the observer  $\Theta$  and enters the future wedge  $F$ , the observer receives no further information about future configurations of  $\phi$ , and all that the observer can do is to estimate the probabilistic distribution  $P[\phi]$  of  $\phi$  beyond the horizon. The maximum ignorance about the field can be represented by maximizing the Shannon information entropy  $h[P] = -\sum_{i=1}^n P[\phi_i] \ln P[\phi_i]$  of the possible field configurations  $\{\phi_i(x)\}$ ,  $i = 1 \cdots n$ .

In Ref. [22] it was shown that the probability is

$$P[\phi_i] = \frac{1}{Z} \exp[-\beta H_R(\phi_i)], \quad (8)$$

where  $\beta$  is a Lagrangian multiplier, and the partition function

$$Z_R = \sum_{i=1}^n \exp[-\beta H_R(\phi_i)] = \text{tr } e^{-\beta H_R}. \quad (9)$$

The equivalence of  $Z_R$  and a quantum partition function for a scalar field in the Euclidean flat spacetime (say  $Z_Q^E$ ) is the famous Unruh effect [35]. A continuous version of Eq. (9) is

$$Z_R = N_0 \int_{\phi(0)=\phi(\beta)} D\phi \exp \left\{ - \int_0^\beta d\tilde{\eta} \int_{r>0} dr dx_{\perp} ar H_R \right\}. \quad (10)$$

By changing integration variables as  $\tilde{r} = r \cos(a\tilde{\eta})$ ,  $\tilde{t} = r \sin(a\tilde{\eta})$  and choosing  $\beta = 2\pi/\hbar a$  the region of integration is transformed into the full flat spacetime. This corresponds to the Unruh temperature  $T_U = \hbar a/2\pi k_B$ , where  $k_B$  is the Boltzman constant. Then, the partition function becomes that of an euclidean flat spacetime;

$$\begin{aligned} Z_Q^E = N_1 \int D\phi \exp \{ & - \int d\tilde{r} d\tilde{t} dx_{\perp} \left[ \frac{1}{2} \left( \frac{\partial \phi}{\partial \tilde{t}} \right)^2 \right. \\ & \left. + \frac{1}{2} \left( \frac{\partial \phi}{\partial \tilde{r}} \right)^2 + \frac{1}{2} (\nabla_{\perp} \phi)^2 + V(\phi) \right] \}, \end{aligned} \quad (11)$$

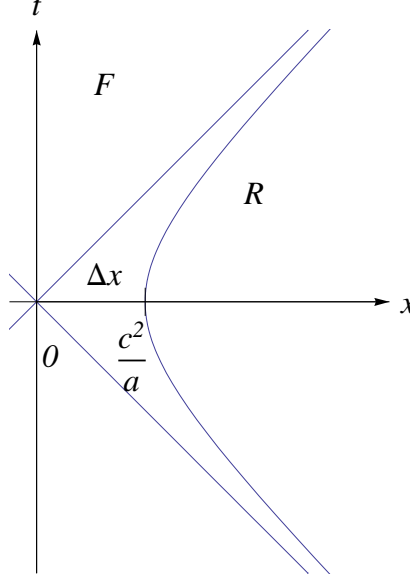


FIG. 1. Rindler chart for the observer  $\Theta$ . The spacetime is divided into two causally disconnected regions  $F$  and  $R$  by the Rindler horizon. If  $\Delta x = c^2/a$ , the test particle is at the horizon for the observer who would see the particle cross the local Rindler horizon.

Thus, the conventional QFT formalism is equivalent to the purely information theoretic formalism for loss of information about field configurations beyond the Rindler horizon, and the thermodynamic nature of QFT and entropic gravity naturally arises in this formalism. The quantum fluctuation is actually thermal for the Rindler observer.

From  $Z_R$  one can obtain various thermodynamic relations between quantities such as  $E$  (the total energy inside the horizon) or  $S$  (the entropy inside the horizon). The free energy  $G = E - T_U S$  from the partition function is expressed as  $G = -\frac{1}{\beta} \ln Z_R$ . Since the maximum entropy is achieved when  $G$  is minimized (i.e.,  $dG = d(E - T_U S) = 0$ ), we notice that the maximum entropy condition due to the information loss, that led to quantum mechanics, yields a condition

$$dE = T_U dS \quad (12)$$

for the fixed Unruh temperature. This seems to be the origin of the relation,  $dE_h = T dS_h$  used in Verlinde's formalism and Jacobson's formalism. It could also explain the first law of thermodynamics in black hole physics [25] and the cosmic expansion.

In our formalism, the holographic entropy used by Verlinde is originated from the loss of information about the bulk field rather than about the exotic matter on the boundary like a string or a brane, and the maximum entropy condition is equivalent to the quantization condition. The relation implies that small energy  $dE$  of matter crossing the horizon induces an increase of the horizon entropy

$$dS = dE/T_U. \quad (13)$$

. This equation means that if we put the more matter into the horizon, the harder we can guess their configurations. The entropy and energy for the horizon are just those of field inside the horizon. In consideration of the definition of the horizon as an information blockade, this interpretation is plausible. We do not need to assume unidentified DOF on the horizon to explain the entropy. The thermodynamic nature of entropic gravity arises from the the very quantum nature of QFT.

Let us obtain the semiclassical limit of this system. The classical field  $\phi_{cl}$  corresponds to the saddle point that gives the largest contribution to  $Z_R$ . This also corresponds to extremizing the Euclidean action in  $Z_Q^E$ . Then, the ordinary semiclassical approximation using the Gaussian integral is  $Z_R \simeq C \exp[-\beta H_R(\phi_{cl})]$ , where  $H_R(\phi_{cl}) \equiv E_{cl}$  is the energy observed by  $\Theta$  for the classical field satisfying the Lagrange equation and  $C$  is a constant. In this limit the free energy becomes

$$G \simeq -\frac{1}{\beta} \{-\beta H_R(\phi_{cl})\} - \frac{C'}{\beta} = E_{cl} - \frac{C'}{\beta}, \quad (14)$$

where  $C' = \ln C$ . Since  $G = E - TS$ , we immediately notice that  $C'$  is a semiclassical entropy  $S_{cl}$  seen by  $\Theta$ . The minimum free energy condition  $dG = 0$  is now equivalent to  $dE_{cl} - T_U dS_{cl} = 0$ . It explains why classical physics can be obtained from thermodynamics as in Verlinde's approach. The classical field centers at the quantum field fluctuations which maximize the entropy. (See also [36].)

It is straight forward to extend the above results to particle quantum mechanics. Since the conventional point particle quantum mechanics is a non-relativistic and single particle limit of QFT, we expect  $Z_R$  for a particle with mass  $m$  is equal to the quantum partition function for the particle in the Minkowski spacetime

$$Z_Q = N_2 \int Dx \exp \left[ -\frac{i}{\hbar} \int dt \left\{ mc^2 + \frac{m}{2} \left( \frac{\partial x}{\partial t} \right)^2 - V(x) \right\} \right], \quad (15)$$

where we kept the leading rest mass term. Then, as is well known one can associate each classical path  $x(t)$  with classical action  $I(x)$  with a wave function  $\psi \sim e^{-iI(x)}$ , which leads to Schrödinger equation for  $\psi$ . The partition function denotes the uncertainty of the path information. A classical path is the typical path maximizing the Shannon entropy  $h[P]$  of the paths seen by the Rindler observer. Therefore, the entropy associated with Newton's mechanics and the Einstein gravity is related to the path information of particles beyond the Rindler horizon. The information-energy relation (Eq. (12)) still holds, however, in this case  $E$  is the mass of particles inside the horizon and  $S$  is the entropy associated with the paths of the particles.

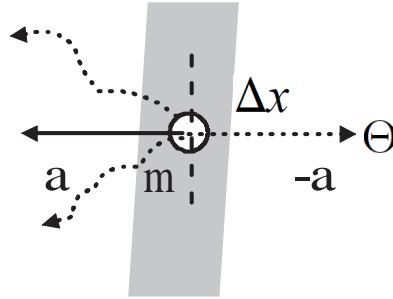


FIG. 2. A test particle with mass  $m$  is accelerating with acceleration  $a$  with respect to an observer instantaneously resting at  $\Delta x$  from the particle. Alternatively, according to the general principle of relativity, we can imagine that the particle is at rest and the observer moves in the opposite direction with acceleration  $-a$ . The observer could see the particle crossing a Rindler horizon (the gray surface) and the future paths of the particle (the dotted curves) become maximally uncertain to the observer. This increases the horizon entropy.

If this interpretation and Verlinde's formalism are consistent, we should be able to reproduce Verlinde's entropy formula (Eq. (1)). To check this consider an accelerating point particle with acceleration  $a$  and mass  $m$  (Fig. 2) and an observer  $\Theta$  at rest at the instantaneous distance  $\Delta x = c^2/a$  from the particle. The distance  $\Delta x$  is special, because, for the observer there,  $\eta$  becomes a proper time and the Rindler Hamiltonian becomes a physical one generating  $\eta$  translation [35]. If we accept the general principle of relativity stating that all systems of reference are equivalent regardless of observer's motion, we can imagine an equivalent situation where the particle is at rest and the observer  $\Theta$  accelerates in the opposite direction with acceleration  $-a$ . Then the observer can see the particle cross the horizon. For this observer there should be information loss. The key idea here is that for an accelerating object we can always assume such a Rindler observer that the object appears to cross the Rindler horizon of the observer.

In the Newtonian limit (when  $mc^2 \gg m(\partial x/\partial \tilde{t})^2$ ), the horizon energy increase is approximately the rest mass energy  $mc^2$  of the particle, hence from Eq. (12) and Eq. (3) the following relations hold.

$$mc^2 = \Delta E = T_U \Delta S = \frac{\hbar a}{2\pi c k_B} \Delta S. \quad (16)$$

This equation means that if we put a particle with mass  $m$  into the horizon, we are uncertain by  $\Delta S$  about the paths that the particle may take. For  $a = c^2/\Delta x$  it gives

$$\Delta S = \frac{2\pi c k_B m \Delta x}{\hbar}, \quad (17)$$

i.e., Eq. (1). (A similar derivation can be found in Culetu's comments [14].) Since the entropy formula is successfully reproduced, we can identify Verlinde's holographic screen as the Rindler horizon and the entropy of the screen  $S$  as the entropy associated with the path seen by the Rindler observer.

There are two ways to derive classical mechanics in this formalism. First, quantum mechanics above reproduces classical Newtonian mechanics in the limit  $\hbar \rightarrow \infty$  and  $c \rightarrow \infty$ . Alternatively, one can also derive Newton's mechanics from the information-energy relation (Eq. (12)) as Verlinde did. One can check that both ways give us the same classical physics in the same limit, and hence, our theory is self-consistent. This fact supports our information theoretic interpretation.

Interestingly, this formalism seems to also hint at the origin of inertia. To understand it, let us return to the rest frame of the accelerating particle. In this frame the particle sees the Rindler horizon following it at a distance  $\Delta x$  and can see part of its spacetime continually disappear behind the horizon. This induces the loss of information about vacuum quantum field. The thermal energy of the horizon is related to the vacuum fluctuation of quantum fields inside the horizon and was suggested to be dark energy [24]. Thus, to accelerate the particle or equivalently to 'drag' the horizon additional energy  $\Delta E$  should be applied to the horizon. This corresponds to an external force  $F = \Delta E / \Delta x$  exerted on the particle due to the action-reaction principle. Thus, the inertia of the particle can be interpreted as *resistance* by the horizon that the external force feels. This dragging force is proportional to acceleration, hence,  $F = ma$ .

Haisch and Rueda [38] proposed a similar idea that inertia is from anisotropic distribution of vacuum fluctuations due to the acceleration and even derived Newton's law. In their model, however, inertia is a consequence of interaction with the electromagnetic zero-point field and depends on the specific interaction the matter has. On the other hand, in our model inertia is related to information loss and does not depend much on the interaction the matter has.

What happens if there is another particle? In that case we need to consider the role of the second particle and this unavoidably leads to the law of universal gravitation described in the next section.

### III. ENTROPIC GRAVITY FROM INFORMATION LOSS

Let us reconsider Verlinde's derivation of the Newton's gravity in [3]. Assume that a small test particle with mass  $m$  is at a radius  $r$  from a massive object with mass  $M$  at the center as shown in Fig. 3. The particle has acceleration  $a$  due to the gravity of the object. Verlinde conjectured that for this spherical system the energy of the screen with a radius  $r$  has energy given by the equipartition rule and it is equal to the mass energy  $Mc^2$  inside the screen. Thus, the temperature  $T$  is  $2Mc^2/k_B N$ . Using the number of bits on the screen  $N = A/l_P^2 = 4S_{BH}$ , and  $A = 4\pi r^2$  one can obtain

$$T = \frac{\hbar GM}{2\pi c k_B r^2}, \quad (18)$$

which is equal to the Unruh temperature for a gravitational acceleration. Here,  $S_{BH}$  is the Bekenstein-Hawking entropy

$$S_{BH} = \frac{c^3 A}{4G\hbar} = \frac{\pi r^2 c^3}{G\hbar} \quad (19)$$

which is an information bound a region of space with a surface area  $A$  can contain [39]. Inserting Eq. (12), Eq. (18) and Eq. (1) into Eq. (20) one can easily obtain the Newton's gravity formula

$$F = T_U \frac{\Delta S}{\Delta x} = \frac{GMm}{r^2}. \quad (20)$$

For strong gravity we need to consider curved spacetime effects as in Ref. [2, 20].

The simple derivation of Newton's gravity from thermodynamics is striking and full of suggestions, but what is the origin of this thermodynamics? Similarly to the previous section, we will reinterpret this derivation in terms of Rindler horizons. The equivalence principle allows us to choose an approximately flat patch for each spacetime point. According to the principle one can not locally distinguish the free falling frame from a rest frame without gravity. We can again imagine an accelerating observer  $\Theta$  with acceleration  $-a$  respect to the test particle in the instantaneous rest frame of the particle. Note that this situation is similar to that considered by Jacobson to derive the Einstein equation [2] from thermodynamics at local Rindler horizons. If the observer is instantaneously at the distance  $\Delta x = c^2/a$  from the test particle, the test particle is just crossing the Rindler horizon for this specific observer  $\Theta$ .

As the test particle crosses the horizon the mass of the particle  $m$  should be added to the horizon energy  $E_h$ , because the horizon energy in our formalism is simply the total energy inside the horizon. This induces the increase of the horizon entropy  $\Delta S_h$  by Eq. (13) due to the loss of the information about the paths of the test particle. Therefore,

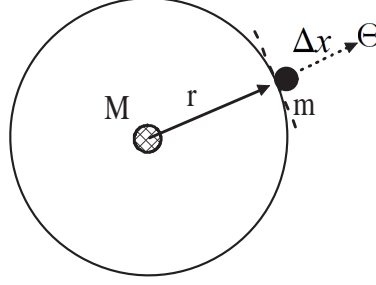


FIG. 3. A test particle with mass  $m$  is at a distance  $r$  from a massive object with mass  $M$  at the center. Consider an accelerating observer  $\Theta$  with respect to the free falling frame with acceleration  $-a$ . If the observer is instantaneously at the distance  $\Delta x = c^2/a$  from the test particle, the observer could see the particle crossing the local Rindler horizon (the dashed line) for the observer.

from Eq. (12)

$$mc^2 = \Delta E_h = T_U \Delta S_h = \frac{\hbar a}{2\pi c k_B} \Delta S_h \quad (21)$$

should hold. Following the argument in the previous section one can obtain the entropy change in Eq. (17) again.

We still need to calculate  $T_U$ . We can safely use the equipartition rule  $E_h = N k_B T_h / 2$  without assuming the specific thermal nature of the boundary physics, because the partition function  $Z_R$  in Eq. (9) represents a canonical ensemble. It is another merit of our formalism. Here,  $N$  is the number of DOF representing the path information of the massive particle inside the horizon. We also rely on the holographic principle. Following Ref. [3] let us assume  $N = 4S_{BH}$ . (In [23] the holographic principle itself was derived within the information theoretic formalism.) Therefore, the horizon energy is

$$Mc^2 = E_h = \frac{N k_B T_U}{2} = 2k_B T_U S_{BH}. \quad (22)$$

From this equation one obtains  $T_U = Mc^2 / 2k_B S_{BH}$  and from Eq. (17) the entropic force in Eq. (20) arises.

It is easy to extend this analysis to the Einstein gravity by following the derivation by Jacobson. We can generalize the information-energy relation  $dE_h = T dS_h$  by defining the energy flow across the horizon  $\Sigma$

$$dE_h = -\kappa \lambda \int_{\Sigma} T_{\alpha\beta} \xi^\alpha d\Sigma^\beta, \quad (23)$$

where  $\kappa$  is the surface gravity,  $\xi$  is a boost Killing vector,  $\lambda$  is an affine parameter,  $d\Sigma^\beta = \xi^\beta d\lambda dA$ ,  $dA$  is a spatial area element, and  $T_{\alpha\beta}$  is the energy momentum tensor of matter distribution. (We set  $c = 1$ .) Using the Raychaudhuri equation one can denote the horizon area expansion  $\delta A \propto dS_h$ , and the increase of the entropy as

$$dS_h = \eta' \delta A = -\eta' \lambda \int_{\Sigma} R_{\alpha\beta} \xi^\alpha d\Sigma^\beta, \quad (24)$$

with a constant  $\eta' = 1/4\hbar G$  [2].

By inserting Eqs. (23) and (24) into Eq. (12) with the Unruh temperature  $T_U = \hbar\kappa/2\pi$  one can find  $2\pi T_{\alpha\beta} \xi^\alpha d\Sigma^\beta = \hbar\eta' R_{\alpha\beta} \xi^\alpha d\Sigma^\beta$ . Due to the maximum entropy principle applied at the horizons, for all local Rindler horizons this equation should hold. Then, this condition and Bianchi identity lead to the Einstein equation

$$R_{\alpha\beta} - \frac{R g_{\alpha\beta}}{2} + \Lambda g_{\alpha\beta} = 8\pi G T_{\alpha\beta} \quad (25)$$

with the cosmological constant  $\Lambda$  [2].

Therefore, we conclude that the Einstein equation simply describes the loss of information about matter crossing local Rindler horizons in a curved spacetime. The holographic screens in Verlinde's formalism are actually local Rindler horizons for accelerating observers relative to the test particle. Albeit simple, this identification could easily explain many questions on Verlinde's formalism and provide better grounds for the theory. The entropy-distance

relation (Eq. (17)) is naturally derived, and the use of Unruh temperature is justified, because the holographic screen is a set of Rindler horizons. This shows the interesting connection between Jacobson's model [2] or the quantum information theoretic model [20, 21] to Verlinde's model.

However, there are also several distinctions between Verlinde's original model and our information theoretic interpretation of the model, which help us to resolve the possible difficulties of entropic gravity [37]. First, in our theory, spacetime is not necessarily emergent and the particle just crosses the horizon rather than merges with it. Our theory relies on more conventional physics such as QFT besides information theory than string theory. Second, in our theory the entropy change happens only after the particle crosses the horizon. This allows a more straight derivation of the entropy-distance relation and helps us to avoid the purported problem associated with ultra-cold neutrons in the gravitational field [40]. Kobakhidze argued that the entropy change in Eq. (1) tells us that the evolution of the particle approaching the screen is non-unitary and this is inconsistent with the neutron experiment. However, in our theory the entropy of the screen increases only when the particle crosses the horizon, and in the rest frame of the particle this process is unitary, thus the problem does not occur. Third, in Verlinde's theory the holographic screens correspond to equipotential surfaces, while in our theory they correspond to isothermal Rindler horizons (i.e., with the same  $|a|$ ). Finally, since the Rindler horizons are observer dependent, there is no observer-independent notion of the horizon entropy increase in our theory. Therefore, we do not need to worry about the issue of the time reversal symmetry breaking in entropic gravity.

#### IV. DISCUSSIONS

It was shown in this paper that the information theoretic interpretation of quantum mechanics well explain the origin of entropic gravity. We conclude that the holographic screens in Verlinde's formalism are actually Rindler horizons for specific observers accelerating relative to the test particle, and the holographic entropy is from quantum fluctuations. This identification could resolve some issues on entropic gravity and provide a more concrete ground for it. The entropy-distance relation is derived, and the use of the Unruh temperature is automatically justified. It shows the interesting connection between Jacobson's model [2] or the quantum information theoretic model [20, 21] and Verlinde's model. In short, our information theoretic approach supports Verlinde's formalism but with the modified interpretation.

Of course, one can reproduce the results in this paper by simply taking the Unruh effect (i.e., starting from Eq. (9)) and the holographic principle as starting assumptions. This might look more familiar. However, in this case the meaning of the horizon entropy and the role of the holographic screen is less obvious than the information theoretic interpretation.

We also found that inertia and Newton's second law have something to do with Rindler horizons and information loss at the horizons. In our formalism and Verlinde's formalism, inertial mass and gravitational mass have a common origin and hence equivalent. If gravity emerges from information loss, inertia should do too. Otherwise, the equivalence principle could be violated. In this sense information seems to be a fundamental ingredient to explain the origin of mass. This approach might open a new route to quantum gravity.

Compared to the previous works by others, our theory emphasizes the role of information rather than thermodynamics. In a series of work including this paper we showed that information loss at causal horizons is the key to understanding the origin of quantum mechanics, Einstein gravity, and even the holographic principle. The best merit of the information theoretic approach is that it provides us a natural and consistent explanations on the strange connection among these different fields of physics [41].

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